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PREPRINT

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SEISMIC MONITORING SYSTEMS

W. J. Hannon

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This was prepared for submittal to
SIPRI/CLIPS Study on a
Comprehensive Test Ban
Ottawa, Canada
October 23-25, 1986

August 1986

Lawrence
Livermore
National
Laboratory

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The Value of In-Country Seismic Monitoring Systems*

W. J. Hannon

**University of California
Lawrence Livermore National Laboratory
Livermore, CA 94550**

Abstract

In-country seismic monitoring systems are elements of most proposals for monitoring a Comprehensive Test Ban (CTB), and some proposals for monitoring a Low-Yield Threshold Test Ban (LYTTB). These systems are made up of data acquisition and processing hardware as well as procedures ranging from site selection to reporting the technical results to the decision makers. The proximity of the in-country stations to potential evasion sites allows the use of multiple seismic waves at each station to detect and identify evasion attempts. Decoupling poses the greatest monitoring challenge. Even with such systems, earthquakes with explosion-like properties and chemical explosions will produce significant numbers of false alarms. Without verified constraints on the source environment, extensive, validated calibration procedures, significant on-site inspection and the validation of new techniques, the yield estimation properties of such networks are of marginal value. The variability of near source effects possible at low yields poses a particularly significant challenge to yield estimation. The broad spectrum of values of the decision makers (e.g., what is a militarily significant evasion), together with the uncertainties in the estimates of capability make the evaluation of the acceptability of specific systems difficult. Decision analysis is a possible approach to addressing this difficulty.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Introduction

An in-country seismic monitoring system is widely recognized as necessary to obtain an acceptable level of verification for a Comprehensive Test Ban (CTB).¹⁻³ However, even with such a system, some violations could go unrecognized. This fact has lead to the consideration of a Low-Yield Threshold Test Ban (LYTTBT) as a possible alternative.⁴⁻⁷ Some of the proposals for an LYTTB have included the use of in-country monitoring as part of the verification measures.

This paper discusses the value of in-country monitoring systems. It begins with a description of the elements of a generic in-country monitoring system. The verification functions to be performed by such a system are described and performance measures are discussed for both a CTB and a LYTTB. The paper concludes with a discussion of performance measures and the decisions that must be made if the acceptability of the system is to be evaluated. The results obtained from an application of decision analysis to determining the value of specific in-country systems for CTB Monitoring are given as an example of a possible approach to structuring the compliance evaluation process.

In-Country Monitoring as Part of the Verification Process

For the purposes of the present discussion, an in-country seismic monitoring system refers to that part of the verification process in which seismic and geological data are collected from locations within the country to be monitored, the data are analyzed, and the results of the analyses are reported to those assessing all of the technical, military and political information necessary to evaluate compliance and initiate appropriate responses. To deploy and operate such a system, each of the

parties to the treaty must take a number of steps (see Table 1).⁷ Since each party simultaneously monitors and is monitored by the other parties, the table includes tasks to be carried out by the host nation as well as by the monitoring nations. These tasks include site selection, start-up and reporting procedures, as well as the more traditional data gathering and analysis efforts associated with monitoring systems. These are important elements of the system and are worthy of considerably more attention than they have received in the public discussions to date.

The Technology of In-Country Seismic Systems

Proposed in-country seismic monitoring systems involve networks of from 5 to 25-30 seismic stations located at sites within the country to be monitored for an area the size of the Soviet Union.^{2,3,8} The proposed distances between adjacent stations range from less than 1000 kilometers^{2,3} to more than 2000 kilometers.⁸ The general areas in which the stations are to be sited would be selected on the basis of the seismicity of the surrounding regions, proximity to other features that could be exploited for evasion (e.g., salt domes and regions of dry porous material as well as regions of competent rock in which cavities could be constructed to decouple the energy of the explosion from the surrounding earth), the location of permitted test sites (if any) and estimates of the propagation characteristics of the seismic waves. Within the general areas, specific sites would be selected to maximize the signal-to-noise ratios.

The instrumentation proposed for such sites ranges from relatively standard seismic stations^{7,8} to state-of-the-art systems involving seismometers with high frequency response (30+/-15 Hz) deployed in boreholes to reduce surface noise and arrays of more conventional seismometers.^{2,3} Depending on the nature of the

instrumentation that would be installed, the sites would cover areas ranging from one to several tens of square kilometers. The smaller areas would be associated with instruments installed in a single borehole and the equipment on the surface needed to power the station, digitize the data and transmit the digital data to remote data centers. The larger areas would be associated with arrays of closely spaced seismometers. The signals from the individual seismometers would be gathered at a central hub facility and transmitted to remote data centers by equipment similar to that used at the single borehole sites.

Recent proposals to enhance the monitoring capabilities of the single borehole sites by using high frequencies depend on exploiting potential improvements in signal-to-noise properties and discriminating between some explosions and some earthquakes at these frequencies.^{2,3} The extent of the contribution of such high-frequency methods is currently being examined. They may be particularly useful to counter evasion schemes based on cavity decoupling (i.e., muffling the signal from an explosion by detonating it in a cavity).

The arrays take advantage of the fact that the data recorded by the individual sensors can be combined in various ways to form data streams with improved signal-to-noise characteristics for sources and noise in specified directions. Achieving the improvement requires that the signals be coherent over the dimensions of the array, and that the noise be incoherent, or have a different direction of approach, velocity or spectral content than the signal. Since arrays offer the promise of being able to identify the speed of the seismic waves and their direction of approach, the location of the source can be determined and some properties of the source can be estimated. Finally, processing the array data may partition the signals from two sources that are close together in space and time. This feature is important when attempting to counter

the evasion strategy that involves detonating a clandestine explosion immediately after a nearby earthquake.

Future networks may contain both types of stations. The balance that will be required will depend on the eventual determination of their relative performance in specific environments and against specific evasion scenarios. Both technologies can be installed at a single site. Also, the use of high-frequency arrays, as opposed to an array of conventional seismometers colocated with a high-frequency borehole element, is being examined. The basic information about signal and noise coherence at high frequencies needed to evaluate such an installation is currently incomplete.

Functions to be Performed by an In-Country Monitoring System

The data acquisition and analysis elements of both external and in-country seismic systems must be capable of carrying out a number of functions if their performance is to be considered acceptable. The functions include: (1) detecting the seismic waves generated by militarily significant nuclear explosions conducted by an intelligent evader; (2) associating the seismic waves recorded at multiple stations and the multiple seismic waves recorded at a single station with a common source located at a specific location; (3) recording and measuring those properties of the signal that can be used to characterize the strength and properties (e.g., pattern of energy radiation, frequency content) of the source; (4) using the measured properties to estimate the yields of announced explosions in the case of a LYTTB and to discriminate between clandestine nuclear explosions and other events, e.g., permitted nuclear explosions (if any), chemical explosions, rockbursts, and earthquakes in the case of both CTBs and LYTTBs.

The heterogeneity of the earth, the variability of the natural and man-made sources, and the ingenuity of the potential evader will introduce uncertainty into the monitor's ability to detect, locate and identify any given event. This uncertainty then becomes part of the monitor's compliance evaluation process. Evaluation techniques such as decision analysis are applicable to the process.⁹ Similar uncertainties affect the potential evader's ability to carry out successful evasion. However, the evader's uncertainties are less than those of the monitor because the evader can calibrate the in-country monitoring system and systematically select operating conditions that favor evasion.

Even if an event is detected, the combination of the technical uncertainties and the decision criteria determined by the value judgments of the monitor may not allow the monitor to be highly confident that the event is not a clandestine nuclear explosion or an explosion that has exceeded the threshold in the case of a LYTTB. In these cases, the information from the in-country system will be used to target other national technical means (e.g., satellites) and to help select locations for on-site inspections. Evidence from all means will be combined to form a final evaluation of the unidentified source.

Monitoring Advantages of In-Country Stations

Although the above uncertainties affect both the external and in-country monitoring capabilities, networks of in-country stations offer some significant monitoring advantages because of the proximity of some of the stations to the possible sources. The stations at regional distances from a source (i.e., stations at distances less than 2000 km) record multiple seismic waves which, in general, have larger amplitudes

and higher frequency content than the seismic waves from the same source recorded by stations at teleseismic distances (see Figure 1).

The multiplicity of waves results from the variety of paths that energy can follow as it travels in the earth's crust and upper mantle from the source to the monitoring stations. The energy recorded at the station as a particular seismic wave follows a path that left the source at a specific angle. If the individual waves recorded at regional stations can be identified, then, in effect, they provide different windows into the pattern of energy emitted by the source. These different views of the source offer the possibility of improved discrimination among source types. This is a topic of active research.¹⁰

The larger amplitudes and increased frequency content of the regional seismic waves reflect the reduced effect of attenuation and the presence of scattering over the shorter shallower paths. The effects vary from path to path, and the causes of the variations in the observations are topics of current research. Also, because the noise tends to decrease with increasing frequency in the 1 to 50-Hz range, the signal-to-noise ratio could increase at high frequencies even if the high frequency propagation is less efficient than claimed. The extent of the contribution of high frequency waves to verification will also depend on the variability of the high-frequency content of the sources. This, too, is a topic of current research. When compared to external stations, in-country seismic systems will provide improved detection and discrimination in almost all environments.

In-Country Stations vs Specific CTB Evasion Techniques

In-country stations are valuable for monitoring a CTB because of their ability to counter specific evasion techniques. Three techniques have been extensively discussed:

(1) simulating earthquake waveforms by detonating multiple nuclear explosions appropriately distributed in time and space; (2) hiding the signals from the clandestine explosion in the signals of an earthquake; (3) reducing the signals from the clandestine explosion by detonating it in dry, porous material or in a cavity. In each case teleseismic stations are of limited benefit in detecting and/or identifying the clandestine explosions.^{11,12}

The in-country systems are able to effectively counter the multiple explosion scenario by comparing the pattern of arrival times, relative amplitudes, and frequency content of the multiple regional waves recorded by the network with the patterns expected from earthquakes in the same region. For example, the spatial and temporal distribution of the explosions may be able to mimic the sequence and properties of waves from a shallow earthquake for one range of azimuths and distances but not another. The sampling of the wave field provided by the in-country network will detect these variations. Furthermore, the broader frequency range recorded by the in-country network provides a means to discriminate between the relatively uniform frequencies generated by the individual explosions representing specific waves and the characteristic frequencies of the waves they are intended to mimic.

These same properties of the network allow the in-country stations to effectively counter the hide-in-earthquake scenario. The differences between the relatively low-frequency content of a teleseismic earthquake and the high frequencies of an explosion even at teleseismic distances allow comparatively straightforward separation of the two signals by filtering the records (Figure 2).¹³ Regional earthquakes and nearby explosions pose a more difficult problem both to the evader and to the monitor. The evader has to wait until an earthquake occurs near the explosion site and then

determine the location and ultimate magnitude of the earthquake in a relatively short time. These time and location constraints are significantly reinforced by the proximity of the in-country stations. Including arrays in the network enhances the ability of even a single site to carry out the spatial resolution of two sources. These increased limitations on the separation between the explosion and the earthquake restrict the opportunities to exploit large earthquakes that could overwhelm the recording at key stations. If the waves from both sources are recorded (that is, the earthquake does not saturate the recording system), then the use of frequencies above even 5-10 Hz will allow the signals from the two sources. However, improvements in earthquake prediction, earthquake triggering, or the exploitation of earthquake swarms or aftershock sequences could make this scenario more attractive to the potential evader. However, the evader's logistical problems are still great, and the in-country stations significantly increase the probability that the evasion will be detected.

In large measure, the in-country network necessary to acceptably monitor a CTBT is determined by the third evasion method--decoupling, in which the explosion is detonated in dry, porous material or in a large cavity, reducing the seismic signals transmitted into the earth. Figure 3 illustrates the reduction in seismic magnitude that occurs as a result decoupling. It also shows the detection performance of some representative monitoring networks. The figure shows that a 1-kt, fully decoupled explosion is equivalent to a seismic event with a magnitude near two, and that a similar explosion detonated in dry porous material would have a magnitude in the low threes. Estimates of the detection capability of worldwide networks⁸ indicate that such small magnitudes would, in effect, be invisible to them. Current analyses^{2,3} estimate that

in order to monitor an area the size of the Soviet Union, 25-30 high-performance in-country stations are required to detect a 1-kt event decoupled in a cavity. Fewer stations could detect such explosions fired in dry, porous material (see Figure 4).² (Note--such material is not thought to be very widespread in the Soviet Union, but our knowledge of Soviet geology is quite limited.)

The efficiency of the discrimination process at these low levels is a topic of current research.^{14,15} The best discriminant performance in correctly identifying earthquakes less than magnitude 4 we have seen at relatively high signal-to-noise ratios approaches 96 per cent¹⁴, assuming that such methods approach 96 per cent efficiency for networks operating near their detection threshold, and given the estimates of the number of shallow earthquakes in the Soviet Union each year as a function of magnitude¹⁶, the annual number of undistinguishable earthquakes at each magnitude level is shown in Table 2. Even given such optimistic discrimination a network whose detection threshold approaches magnitude two would have 100-400 unidentified earthquakes that could not be distinguished from explosions.

In addition, the many chemical explosions greater than 20 tons conducted each year will pose significant discrimination problems. It may be possible to address the compliance issues raised by chemical explosions greater than several hundred tons through inspection measures similar to those described in the unratified treaty governing Peaceful Nuclear Explosions.¹⁷ The smaller explosions, whose seismic signals are similar to those from a 1-kt decoupled nuclear explosion, are too numerous to handle by such measures. Therefore, unless very efficient discrimination measures are found for such events, they will be a continuing source of concern.

In-Country Systems vs LYTTB Evasion

In-country networks for monitoring a LYTTB (which would allow nuclear explosions at selected sites if the explosions have yields less than the threshold) may be needed if the threshold is low enough. The networks could perform two functions: yield estimation for the explosions at the permitted sites, and monitoring for clandestine explosions conducted away from the permitted sites. In the former case, the characterization of the size of the source provides the required monitoring function. In the latter case, the monitoring functions are qualitatively similar to those proposed for a CTBT. However, for thresholds greater than a few kilotons the monitoring requirements can be relaxed somewhat because evasion will almost certainly involve yields greater than those that can be detonated at the designated test site.

Figure 3 shows that explosions with yields of about 5-10 kt detonated in hard rock and well-coupled to their surroundings will be detected by external networks with good signal-to-noise ratios. Assuming that validated magnitude-yield relationships have been determined for the site to be monitored, such networks should be able to estimate the yields of such events with accuracies similar to but less than those achievable at higher yields. However, such explosions can also be detonated in dry, porous material or partially decoupled in cavities. If suitable on-site inspection measures were instituted, these situations could be identified so that the possibility of systematic errors could be reduced. Even if the situations were recognized, the signal-to-noise ratio for these decoupled events would be low enough so that the accuracy of the yield estimates made by external stations would be significantly degraded. In addition, the uncertainty would increase because of the increased variability in coupling that is

possible in such media and because of the effects of variation in depth of burial and proximity to the water table on the waveforms currently used to estimate yields.

A network of in-country stations surrounding the test site might improve the accuracy of the yield estimates through the use of regional seismic waves such as Lg (see Figure 1).¹⁸ Such methods are still being researched and appear to depend somewhat on the source and receiver locations. The network would have to be calibrated by a series of explosions whose yields and source regions were validated. New explosions would be required to be detonated near the calibration events and on-site inspections would be necessary to insure that the materials in the source region were similar for the calibration and the new events whose yields are to be estimated. Even with such measures increased uncertainties due to depth of burial and material heterogeneity would exist.

For thresholds less than a few kilotons, the uncertainties in these in-country measurements resulting from these factors would make it difficult to confidently distinguish between explosions at the threshold and explosions 3-5 times larger (at the two sigma level). Thus, with the possible exception of using waves such as Lg for explosions for well-characterized, constrained environments, in-country stations will not provide definitive yield estimates for a LYTTB with thresholds less than a few kilotons. If highly accurate estimates of yields are desired, means other than seismic (e.g., hydrodynamic)¹⁹ will have to be used. However, in-country stations deployed for yield estimation under such a LYTTB would gain experience for off-site monitoring that might be of value under a CTBT.

In-country stations can play an important role in detecting and identifying clandestine explosions conducted at locations other than the test sites permitted under

a LYTTBT. Partial decoupling of explosions with yields less than 20-30 kt could produce signals which would not be identified by an external network. Thus in-country stations would be required to identify such explosions. For a 1-kt threshold, the in-country network required to prevent significant off-site testing would be nearly equivalent to that necessary to monitor a CTB.

The above discussion has not addressed the monitoring issues raised by permitting peaceful nuclear explosions in conjunction with a LYTTB. Almost every aspect of yield estimation is made worse for such explosions because of the problems associated with calibration. It would be necessary to use yield estimation techniques using the speed of shock waves to obtain accurate yield estimates. Such measures should be introduced at relative yields less than those currently introduced in the unratified treaty governing PNEs conducted in conjunction with the TTB. In-country systems could play a useful role in monitoring such explosions by limiting the opportunities to conduct simultaneous clandestine weapons tests at nearby locations. This contribution could be particularly useful for preventing nearby clandestine explosions in conjunction with group explosions permitted under the PNE treaty.

What is Acceptable Verification?

To discuss the value of in-country monitoring systems to the overall verification effort, we must consider the qualities required for acceptable verification. (I have chosen to use the adjective "acceptable" rather than the more common qualifiers "adequate" and "effective"²⁰ to emphasize the role that value judgments play in an evaluation process whose fundamental measurements are subject to uncertainty.) Three

qualities have been mentioned, either explicitly or implicitly, for evaluating verification:^{21,22} (1) militarily significant violations must be recognized in time to mount an appropriate response; (2) the false alarm rate must be low enough to maintain the monitor's confidence and not degrade the potential evader's incentive to comply; (3) the system's capability, when combined with the evader's perceptions of the costs of being caught vs the benefits of successful clandestine testing, should deter evasion attempts.

Translating these elements into operational measures of success requires a combination of military, technical and political judgments. From a practical viewpoint, one of the most important of these judgments in many current discussions is the definition of a militarily significant violation. Forming this judgment involves estimating the immediate and long-term impacts of a test ban and of the asymmetry introduced by evasion on such diverse but interrelated elements as stockpile reliability, preservation of infrastructure, ability to respond to developments in the nonnuclear capabilities of the weapons systems, survivability and safety. These impacts must be identified by the military community and evaluated by the decision makers in the broader context of both relative and absolute national security.

Another factor that must be considered is the number of false alarms that can be tolerated by both the monitor and the potential evader. These false alarms erode the confidence of the monitor and remove an incentive for the potential evader to comply. The false alarm levels considered acceptable are also related to any negotiated provisions for on-site inspections.

A third factor that must be estimated is the value system of the potential evader. The evader presumably attaches some cost to an unsuccessful attempt at evasion and

some value to a successful one. These, and related values (e.g, the value attached to acknowledged compliance and the value attached to compliance in the presence of false alarms), may vary with time. Given such values and assessments of the efficiency of the monitoring systems, expected costs and benefits can be estimated and deterrence can be evaluated. Informal evaluations of this type have been invoked to argue, for example, that a 30 per cent probability of being caught is sufficient to deter evasion attempts.⁷ Such judgments have significant impacts on the acceptability of a given in-country monitoring system.

Many other factors affect the acceptability of an in-country monitoring system. Intrusiveness, cost and negotiability are a few specific factors that have to be considered from both the monitor's and the potential evader's viewpoint. The whole evaluation must take place in the context of the decision makers' view of national security and the threat posed by the nation to be monitored.

Techniques such as decision analysis allow a structured approach to decision making in complex situations that involve both uncertainties in the technical measures and a variety of value judgments. We have been applying this approach to CTBT verification,^{8,23,24} and have obtained preliminary results for a number of cases. For example, Figure 5 compares the relative value of using external monitoring, a network of 10 relatively standard in-country stations and a network of 30 high-performance in-country installations for cases in which cavity decoupling is a viable evasion method and cases in which it is not. The difference in the relative value of the high-performance stations between the two cases is the result of a choice of values that penalizes the high-performance stations for unnecessarily detecting small events (many of which remain unidentified) when cavity decoupling is not a viable option. This

figure represents the results of a number of technical estimates of performance and value judgments. The decision analysis framework treats these as input values that can be chosen by the decision maker. As such, the framework allows parameter studies that identify critical elements in the decision process, and allows the structured comparison of the implications of different value systems. We are beginning a similar structured analysis of the issues associated with LYTTBs.

Conclusions

In-country seismic monitoring systems are composed of data acquisition and data processing hardware and procedures as well as procedures to select sites, calibrate the performance of the system in a new environment, operate the system, and report the results in a form useful to the decision makers.

The value of these systems to monitoring a CTB is derived from their ability to counter evasion scenarios such as using multiple explosions to mimic the signals from an earthquake, hiding the signals from a clandestine explosion in the signals from an earthquake, and reducing the signals from an explosion by detonating it in dry, porous media or in a cavity. The decoupling evasion methods pose the greatest challenge, forcing the monitoring system to detect and identify events down to magnitudes of about two. The presence of high-performance in-country stations (small arrays and/or high-frequency sensors) allows the recording of multiple seismic waves with relatively large amplitudes and high frequencies. In addition, the distribution of the in-country stations allows the wavefield to be sampled at a variety of distances and azimuths. The interlocking information provided by observations allows multiple assessments of the source properties. These multiple assessments provide the basis for identifying

differences between the evasion attempts and other seismic sources.

Even with networks consisting of 25-30 such high-performance stations, some events whose signals are equivalent to a 1-kt nuclear explosion detonated in a cavity will not be detected. Some of those that are detected will not be identified against a background of thousands of small earthquakes. Unidentified earthquakes, of which there could be hundreds, will give rise to false alarms. Chemical explosions will pose severe discrimination problems.

Monitoring an LYTTB requires that the yields of explosions at permitted test sites be estimated with high accuracy, and that clandestine explosions executed away from these sites be detected and identified. This latter requirement is made difficult by the background of earthquakes and chemical explosions in which the signals from the clandestine event would reside. For LYTTBs with thresholds near 1 kt, the off-site monitoring requirements would be similar to those needed to monitor a CTB.

In the absence of extensive calibration limitations on the testing environments supported by on-site inspections, and the validation of promising new techniques using waves such as Lg, in-country monitoring systems are of limited value for yield estimation for LYTTBs with thresholds less than 5-10 kt because of the systematic variation in the seismic signals that can be introduced by variations in depth and emplacement material. However, the yield estimates from in-country systems are unlikely to be as accurate as those made from close-in shock wave measurements.

The presence of uncertainty in the measurements raises the question of what constitutes acceptable verification. Ultimately this is a value judgment encompassing a wide range of factors, including the military significance of successful evasion, the impact of false alarms, the potential evader's value system and many other factors

covering a wide range of military, political and economic issues. The technical results--with their attendant uncertainties--and the value systems of the decision makers--with their differing priorities--can be combined using techniques such as decision analysis. The structuring produced by the use of such techniques allows us to identify important elements in the compliance evaluation process and evaluate the effects of differing or changing viewpoints. Such techniques have been applied to analyze the value of in-country systems to CTB monitoring.

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**Table 1. Steps necessary to deploy and operate
an in-country seismic monitoring system.**

- 1. Determine the properties of an acceptable system:**
- 2. Negotiate:**
 - Prepare proposal**
 - Analyze counter-proposals**
 - Develop responses**
- 3. Exchange and assess pre-installation data:**
 - Prepare geological data package to be handed over**
 - Analyze geological data package received**
 - Revise**
 - Iterate**
- 4. Deploy equipment:**
 - By the country doing the monitoring**
 - Obtain information about sites**
 - Select sites**
 - Select instrumentation for each site**
 - Install and check out equipment**
 - By the country being monitored**
 - Determine acceptability of sites**
 - Monitor installation**
 - Participate in check out**

Table 1. (Cont'd.)

5. Carry out monitoring functions both as monitor and as one being monitored:

**Carry out start-up procedures, e.g., calibrate a network,
site and path characterization**

Compare actual conditions with estimates

Seek changes if mismatch

Operate and maintain equipment

Archive equipment status and seismic data

Process data

Characterize properties of the signals/sources

6. Coordinate with other technical elements:

National technical means

On-site inspections

7. Report results to decision makers:

Events detected

Locations

Estimate of source type

Uncertainties

Ranking

**Table 2. Approximate number of unidentified events per year from
high-performance seismic monitoring systems
deployed in the Soviet Union.**

Detection threshold (m_b)	No. of earthquakes in Soviet Union per year (m_b)	Approx. No. of unidentified earthquakes per year ^a
4.0	100-300	0-10
3.5	270-800	10-30
3.0	700-2000	20-60
2.5	1800-5300	60-200
2.0	4600-14000	100-400

^a Assumes 4 per cent of the earthquakes within 0.5 magnitude units of m_b will not be identified.

Figure Captions

1. Panel (a). Regional seismic waves (recorded at distances less than 2000 km) follow a variety of paths in the crust and mantle of the earth. They exhibit larger amplitudes and higher frequencies than teleseismic waves. Panel (b). A regional seismic record from a well-coupled nuclear explosion at the Nevada Test Site measured at Elko, Nevada (distance: 40 km). The multiple bursts of energy are each associated with a distinct path. In general, the earlier arrivals are associated with the deeper paths in the heterogeneous crust and upper mantle. Panel (c). A teleseismic record for the same event from a high quality array station located in Norway (distance: 7935 km). Smaller amplitudes and fewer waves lessen the usefulness of such waves for small events.
2. Differences in frequency content can be used to detect explosions in the coda of an earthquake. Panel a shows a Norwegian recording of the signal from an earthquake in Kamchatka together with the signal from an explosion at Semipalatinsk.¹³ The explosion's signal at about $t=100$ s is not readily identified on this record (pass band 1.2-3.2 Hz). Panel (b) shows the same signal processed with a filter that emphasizes the frequencies from 3.2-5.2 Hz. The signal from the explosion at about $t=100$ s is readily discernible.
3. Magnitude-yield relationships from Nevada Test Site explosions and estimated detection thresholds for in-country networks deployed in the Soviet Union (90 per cent) confidence of detecting four or more waves) are shown for representative media and networks, respectively. The dashed lines indicate that the data are lacking or subject to significant uncertainty. Note that in areas that are older and

more stable than the Nevada Test Site, the magnitudes of the same explosion could be several tenths of a unit higher.

4. The estimated detection capability of an in-country network varies as a function of the number and type of stations deployed. The calculation requires a 90 per cent probability of detecting four or more waves. Uncertainties of several tenths of a magnitude unit are possible because the signal and noise properties in the Soviet Union are unknown. The small box at the left shows the upper range of the estimate for a 1-kt explosion decoupled in a cavity. The dashed line shows the values that might be observed in an older, more stable region. Note that approximately 30 high-performance stations (arrays or possibly high-frequency stations) appear to be required to detect 1 kt with high confidence.
5. The value of different networks depend on the evasion threat. The base case corresponds to 30 high-performance in-country stations or 10 simple stations or external stations operating in an environment where decoupling is feasible. If we assume that all decoupling is not feasible, the NTM system is the most attractive because it can detect all the militarily significant tests at no extra cost. Also, if we assume more than three times as many small earthquakes as in the base case, the NTM system again is the most valuable because it is least liable to produce false alarms. Many assumptions are made in these estimates. These can be examined using the decision analysis framework.

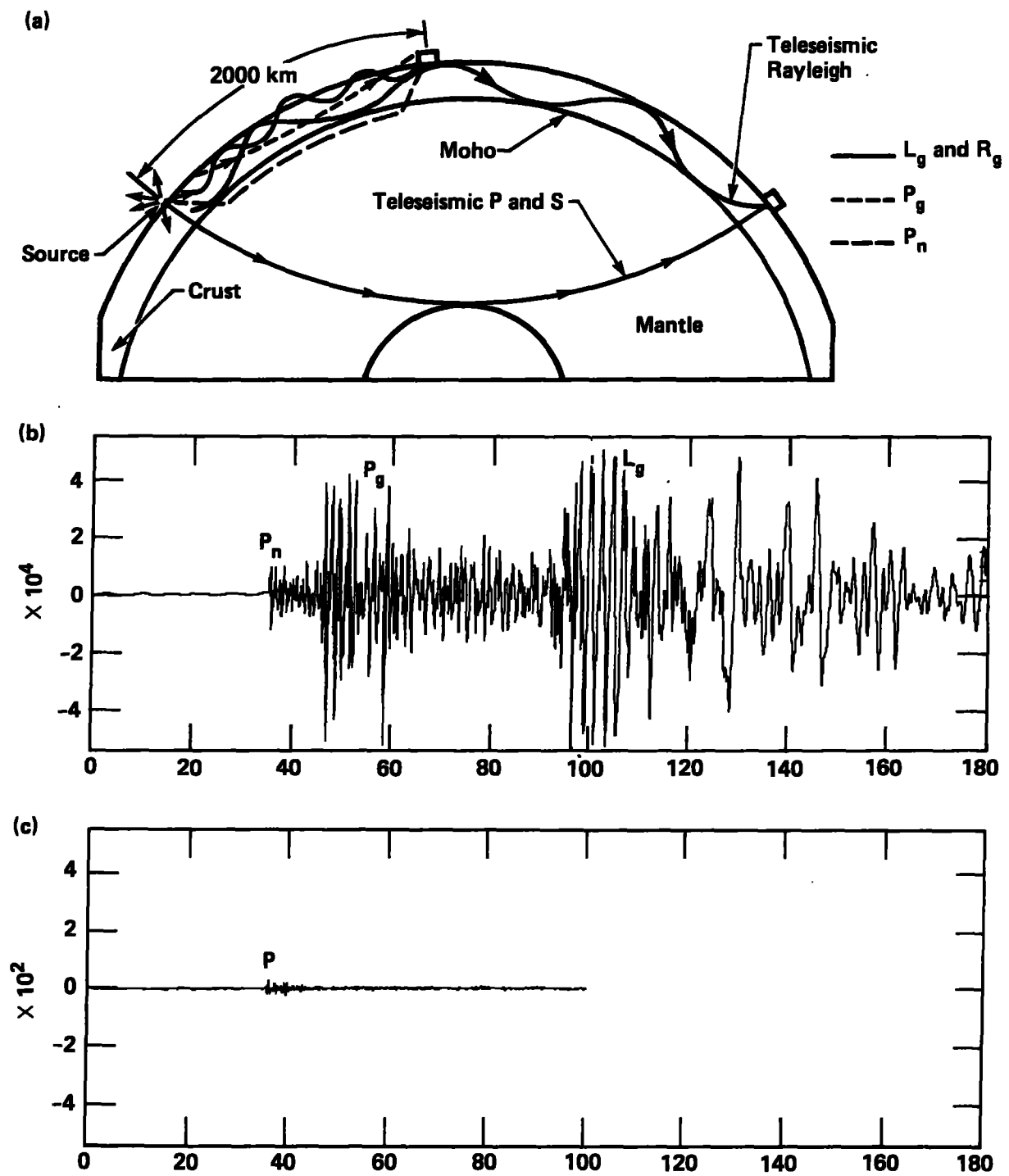


FIG. 1

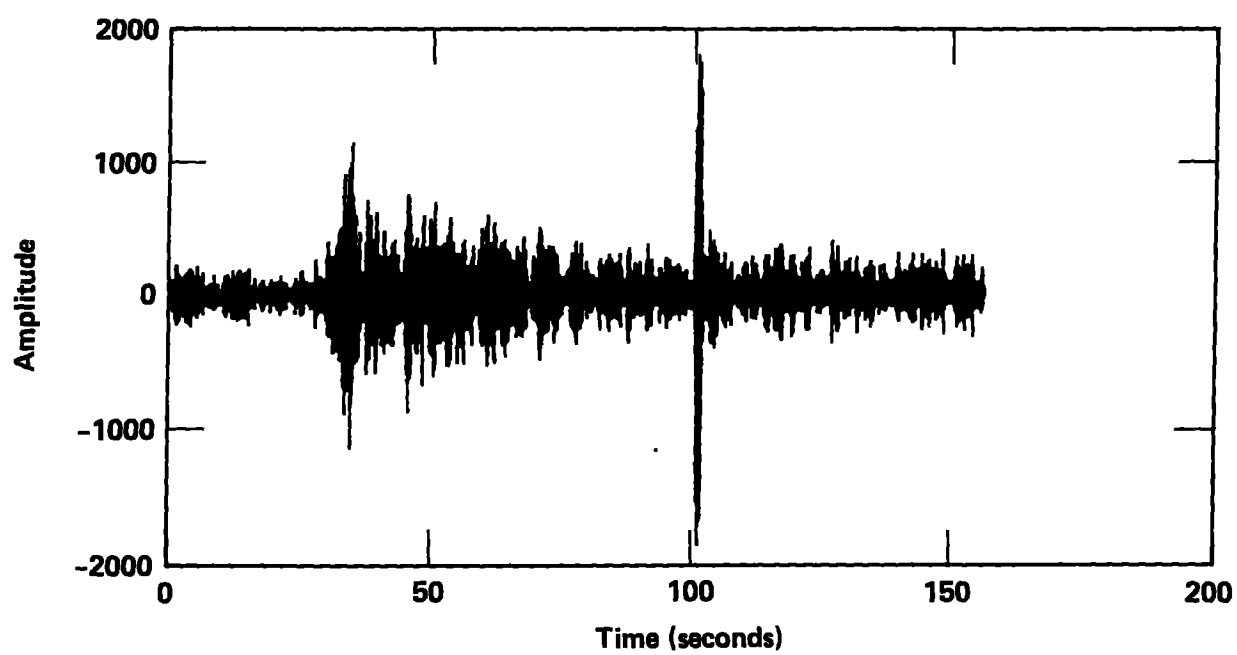
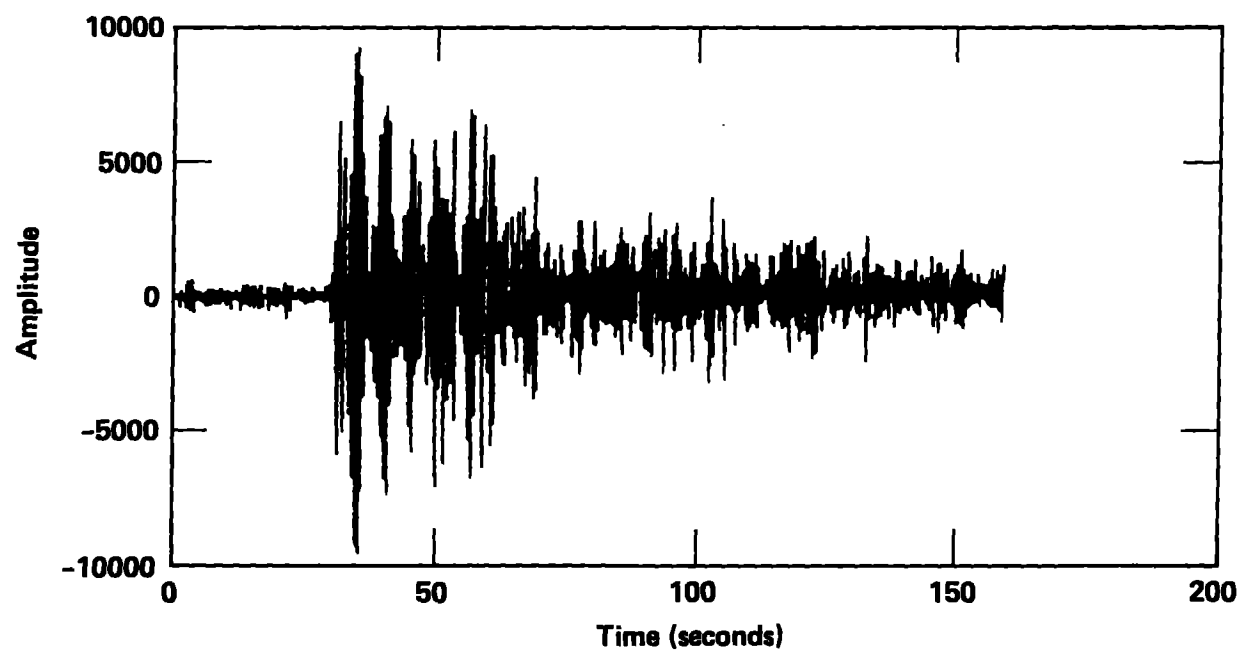
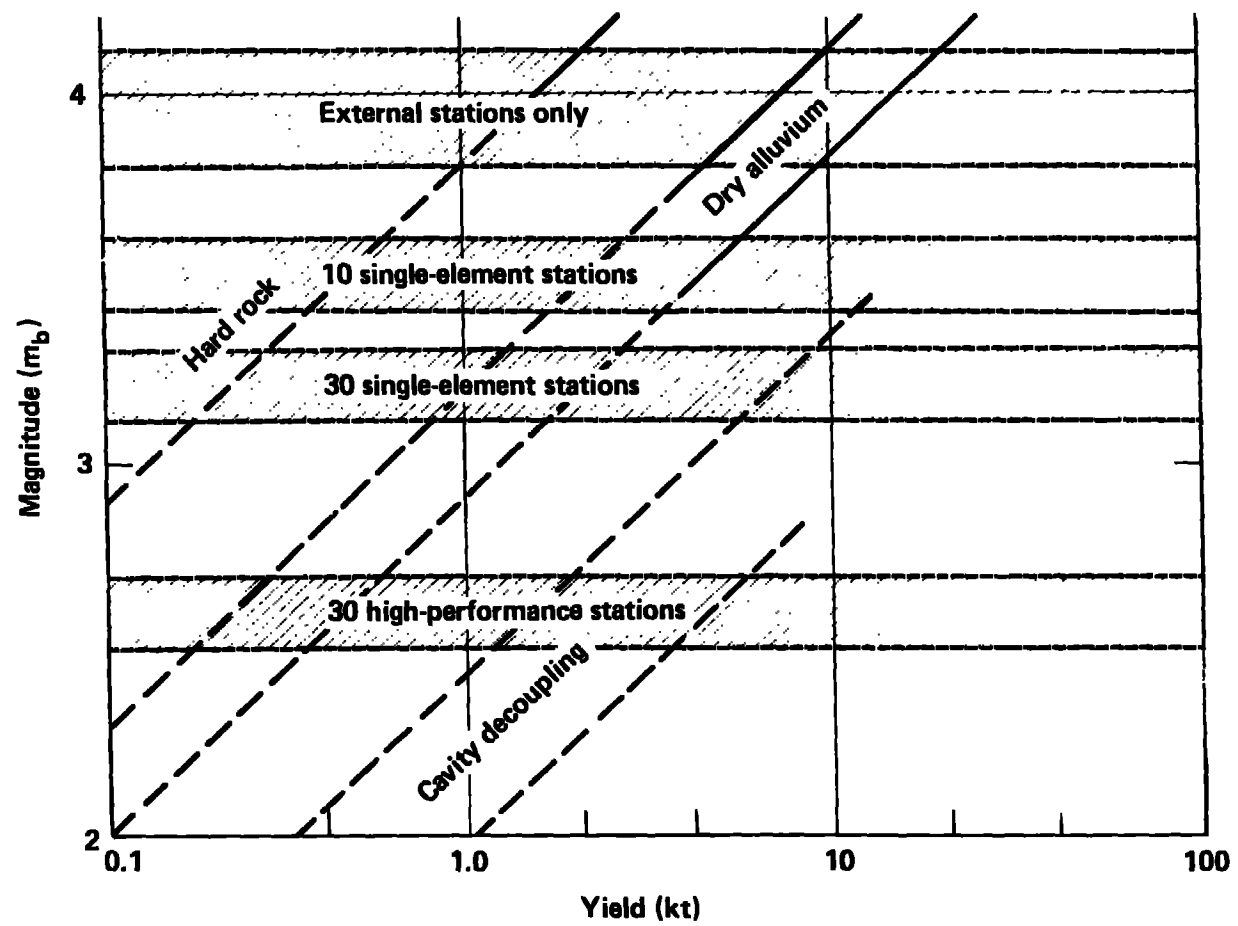


FIG. 2



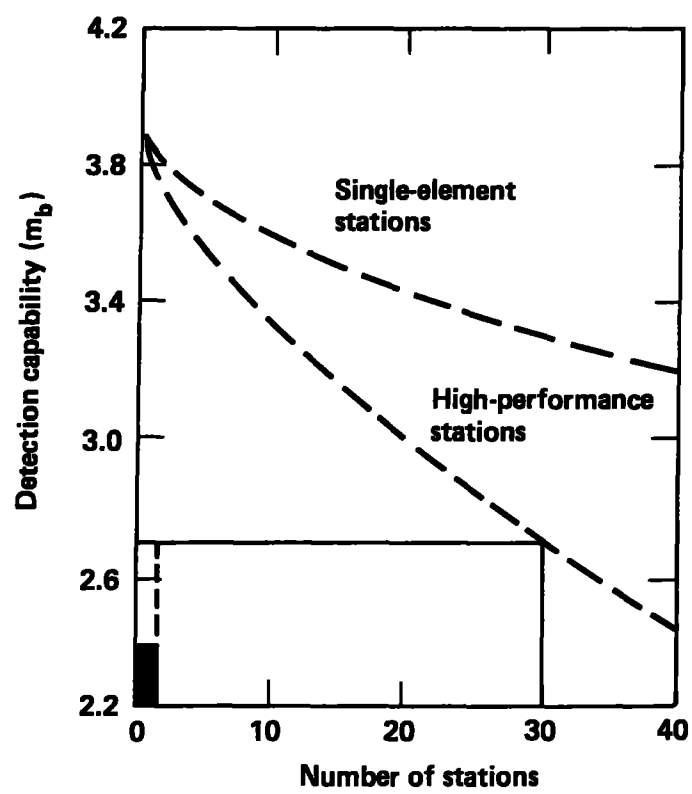


FIG. 4

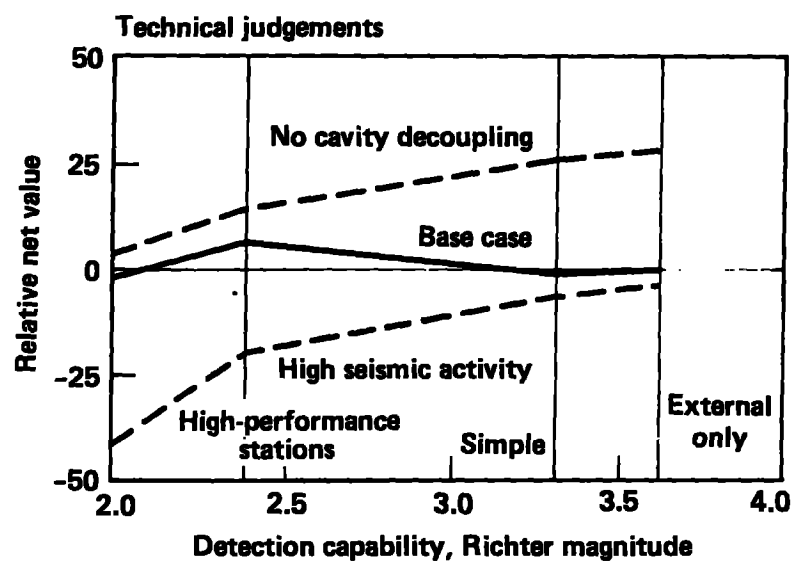


FIG. 5

